

## Response of runoff and suspended load to climate change and reservoir construction in the Lancang River

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### ABSTRACT

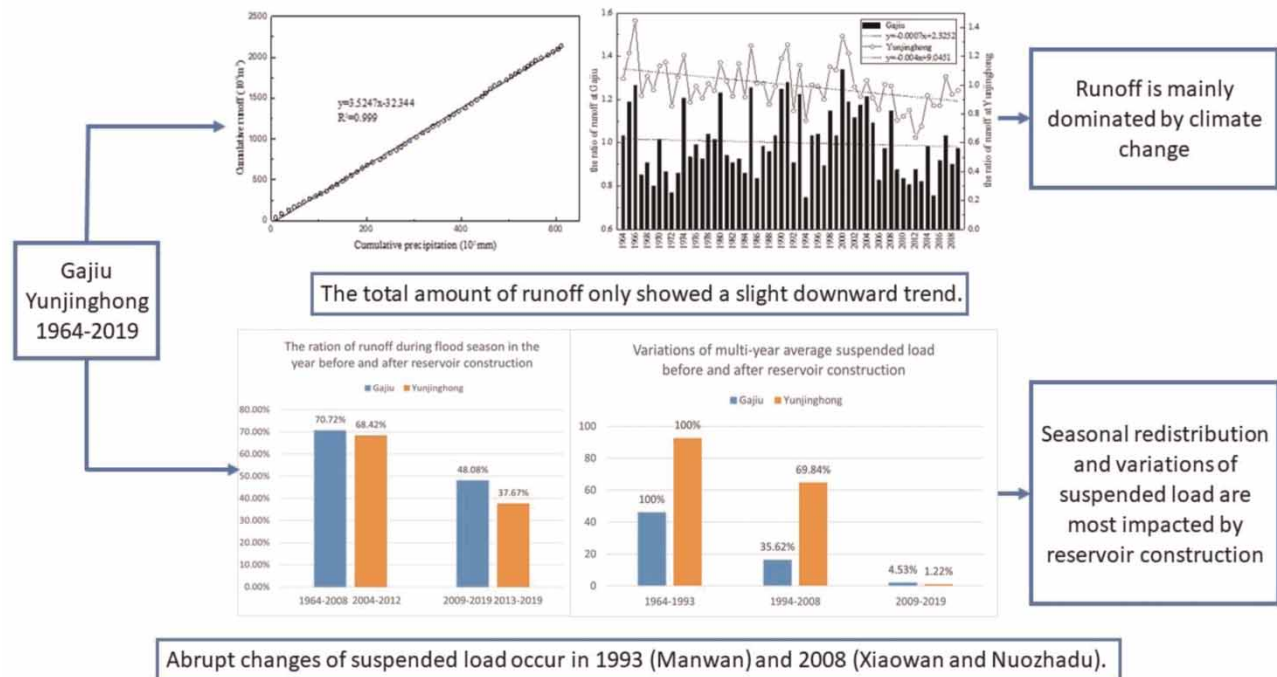
With the operation of six cascade reservoirs, the flow regime and sediment discharge of the Lancang River have changed greatly. The changes of runoff and suspended load have attracted extensive attention. The hydrological data of Gajiu and Yunjinghong stations in Lancang River from 1964 to 2019 were analyzed by using wavelet analysis, double mass curve and abrupt change analysis. The temporal trends in runoff and suspended load were evaluated. Results revealed that the reduction of suspended load was much more profound than the change of runoff. There was a slight downward trend in annual runoff due to climate change. After the completion of Xiaowan and Nuozhadu reservoirs, the proportion of runoff in flood season decreased by 22.64 and 30.75%, respectively. Wavelet analysis was used to reveal the characteristics of runoff evolution. With the operation of reservoirs, suspended load showed abrupt changes in 1993 and 2008. The amount of suspended load during 2009–2019 decreased by 95.47–98.78% compared with that before the reservoir construction. This paper presents the latest quantitative study on the temporal variation of runoff and suspended load since the completion of Xiaowan and Nuozhadu reservoirs, which is of great importance for guiding the operation of reservoirs and maximizing the value of the whole Lancang-Mekong River basin.

**Key words:** runoff, climate change, Lancang River, reservoirs, suspended load

### HIGHLIGHTS

- Variations of runoff and suspended load during 1964–2019 in Lancang River were first quantified in detail after Xiaowan and Nuozhadu reservoirs were completed.
- The total amount of runoff was dominated by climate change, while reservoir construction mainly influenced the annual process of runoff.
- Suspended load exhibited abrupt changes in 1993 and 2008 and the reduction reached 95–99% after the reservoir construction.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Being the largest river in Southeast Asia, the changes of runoff and suspended load in the Lancang-Mekong River have attracted great attention as it is endowed with abundant hydraulic resources (He *et al.* 2005). Due to energy demand and economic growth, extensive hydropower development has been imposed on the river basin, resulting in great changes of streamflow and suspended load (Farrokhi *et al.* 2020, 2021; Anaraki *et al.* 2021; Farzin & Anaraki 2021). Flow regimes are considerably affected by large amounts of sediments and nutrients trapped in reservoirs (Kummu *et al.* 2010; Ehteram *et al.* 2018). Thus, the changes in hydrological regime and sediment discharge of the Lancang River have become the focus of relevant research (Zhao *et al.* 2013). Variations in discharge and suspended load have been studied extensively (Stanford *et al.* 1996; Lajoie *et al.* 2007; Hu *et al.* 2008; ICEM 2010; Lu *et al.* 2015). Among them, the impacts of climatic change and reservoir operation are the most studied and the most influential (Keskinen *et al.* 2010). Other factors such as land use change and soil erosion are also investigated (Liu *et al.* 2013a, 2013b).

Table 1 presents recent research about the changes of water discharge and sediment flux as well as their driving factors in the Lancang-Mekong River. Most of the research focused on the variation of streamflow and how the streamflow was affected by human activities and climate change (Zhao *et al.* 2012a, 2012b; Tang *et al.* 2014; Li *et al.* 2017; Liu *et al.* 2018; Han *et al.* 2019). Zhao *et al.* (2013) further revealed that meteorological variables were closely related to runoff and were affected by dam construction and climate change. The changing sediment loads of Mekong River were also studied (e.g. Walling 2008). However, few researchers have investigated both the changes of suspended load and runoff in Lancang River within Yunnan Province (You 1999; Liu & He 2012; Zhai *et al.* 2016). Existing research showed that the change of suspended load was more significant than that of runoff under the impact of human activities and climate change. Therefore, it is necessary to conduct further research on the changes and trends of both streamflow and sediment load in the Lancang River.

Downstream changes and the impacts of upstream hydropower development on the Lower Mekong have been studied in various researches (Fu *et al.* 2008; Räsänen *et al.* 2012, 2017; Lauri *et al.* 2013). Flow and sediment data of Chiang Saen, Stung Treng and other downstream stations were more frequently analyzed to better understand the changes in the Lower Mekong (Lu & Siew 2006; Kummu & Varis 2007; Binh *et al.* 2020). Other studies have focused on the whole Mekong River (Kuenzer *et al.* 2013; Liu *et al.* 2018; Hecht *et al.* 2019). Generally speaking, most studies are concerned about the downstream impacts from the Lancang cascade reservoirs and the changes in the downstream basin. Few studies have

**Table 1** | A summary of previous research on water-sediment change in the Lancang-Mekong River

Authors	Study area	Data period	Methods	Major conclusions
Zhao <i>et al.</i> (2012a, 2012b)	Lancang River	1957–2000	Range of variability approach; Linear regression method; Mann-Kendall test	Hydrologic regimes were influenced by damming and precipitation variations while hydrologic alteration was quite low in the upper Lancang River without a dam.
Zhao <i>et al.</i> (2013)	Lancang River	1957–2000	Evaluation of model performance; Range of variability approach; Mann-Kendall test	Meteorological variables were closely related to runoff and simulative evolution indicated that runoff was influenced by dam construction and climate variation. The hydropower operations have considerably modified the river discharge since 2011.
Zhai <i>et al.</i> (2016)	Lancang River	1964–2010	Mann-Kendall test; Double mass curve; Annual variation analysis	Spatiotemporal changes of runoff and sediment load are dominated by the construction of hydropower stations, land use and precipitation variations.
Tang <i>et al.</i> (2014)	Lancang River	1956–2008	Mann-Kendall test; Back-Propagation Artificial Neural Network model	At the yearly, seasonal and monthly time scales, human activities and climatic variations made different degrees of contribution on the changes of streamflow.
Räsänen <i>et al.</i> (2012, 2017)	Lancang-Mekong	1985–2010; 1960–2014	Hydrological model; Reservoir cascade optimization model; Distributed hydrological model	Lancang-Jiang cascade increased (decreased) the discharge as well as the range of hydrological variability during the dry season (wet season). The hydropower operations have considerably modified the river discharge since 2011.
Lu & Siew (2006)	Lower Mekong	1962–2000	Water levels and water discharge analysis; Sediment concentration and sediment flux estimation	In the dry season, flows decreased while water level fluctuations significantly increased during 1993–2000. Monthly suspended sediment concentration decreased considerably during 1993–2000.
Liu <i>et al.</i> (2018)	Lancang-Mekong	1960–2013	Mann-Kendall test; Hydrologic budget balance analysis	Precipitation changes were the main reason for runoff changes, and dams in the Lancang River were not enough to impact the annual variation of natural runoff.
Han <i>et al.</i> (2019)	Lancang River	1980–2014	Mann-Kendall test; CREST-snow hydrologic model	Mean annual streamflow decreased significantly during 1987–2014 after the dam construction and climatic change made a greater contribution to streamflow change during 1987–2007 while human activities were the dominant factor during 2008–2014.
Fu <i>et al.</i> (2008)	Upper Mekong	1965–2003	Linear regression; Granger causality; Augment Dickey–Fuller test	Sediment discharge and suspended sediment concentration bear the most significant effects at Gajiu station and lesser at Yunjinghong station; meanwhile, suspended sediment concentration first decreased obviously and then began to recover since 1997.
Liu & He (2012)	Lancang River	1963–2007	Linear regression; Hierarchy analysis method; Factor analysis method; Quantitative evaluation model	The runoff and sediment both exhibit a change process in ‘U-shaped’, but sediment transport has more significant change than runoff due to the cascade construction.
Kummu & Varis (2007)	Lower Mekong	1962–2002	Brune method; Linear regression	Due to the Lancang cascade, the average dry season flow increased and sediment flux decreased in the lower Mekong. The closer to the dams, the greater the changes.

(Continued.)

**Table 1** | Continued

Authors	Study area	Data period	Methods	Major conclusions
Liu <i>et al.</i> (2013a, 2013b)	Lancang-Mekong	1965–2003	Double mass curve	Sediment load reduced considerably at Gajiu station after the construction of Manwan dam, but the reduction was not obvious at Yunjinghong and further downstream.
Binh <i>et al.</i> (2020)	Lower Mekong	1961–2015	Mann-Kendall test; Sen slope; Pettitt test	The reduction of sediment load in the Lancang River was due to sediment trapping in the cascade dams and it has caused great morphological changes in the Vietnamese Mekong Delta.
You (1999)	Lancang River	1955–1987	Linear regression	The change of discharge remained stable while sediment load showed a trend of increase.
Walling (2008)	Lancang-Mekong	1960–2003	Data analysis	There is little evidence of increasing sediment loads at some measuring stations; the overall trends show little evidence of major changes.
Li <i>et al.</i> (2017)	Lancang-Mekong	1960–2014	IHA metrics; Eco-flow metrics; M-K test; Cubic spline smoothing	The construction and initial filling of upstream dams reduced the annual streamflow in the upstream Chiang Saen station, whereas no clear effect was observed in the downstream Stung Treng station.

concentrated on the changes of water and sediment discharges in the Lancang River itself (Liu *et al.* 2013a, 2013b). Among them, there are little detailed and systematic analyses of the changes in streamflow and suspended load.

Overall, the data in the Lancang River within Yunnan Province analyzed in previous research was mainly prior to 2010. After 2010, the two largest completed reservoirs, Xiaowan and Nuozhadu, were not able to be considered in the aforementioned study. Thus, the effect of these reservoirs on the changes of runoff and suspended load remains unclear.

The aim of this paper is to provide an up-to-date quantitative analysis of temporal changes in runoff and suspended load in the Lancang River after the operation of Xiaowan and Nuozhadu reservoirs. The data of annual runoff and suspended load from Gajiu and Yunjinghong stations during 1964–2019 is analyzed. Impacts of reservoir construction and climate change on the inter- and intra-annual variations of runoff and suspended load are also assessed. Previous studies paid little attention to the changes of runoff and suspended load in the Lancang River, but this paper comprehensively analyzes those changes and concentrates more on the Lancang River itself with a quantitative result provided. The data used is the longest and latest time series so far and the obtained results can cover the phased results of previous research. Therefore, it gives a clear and full picture of the changes in water and suspended sediment load before and after reservoir construction. The current status of water and sediment in Lancang River is also presented with the operation of the main six cascade reservoirs. The general trend of runoff changes in the future can be predicted through the analysis of runoff periodicity, which can help understand the dynamic change of water resources and make judgments on the abundance and depletion of water resources. All these can offer comprehensive information for managers to better guide the long-term operation of reservoirs and provide a specific basis for decision-making related to resource allocation. At the same time, this study can provide new evidence for further research on downstream changes of water and sediment and scientific evaluation of transboundary impacts. In this way, the Lancang-Mekong River can maximize its role in serving economic development and people's livelihood of the whole basin.

## 2. MATERIALS AND METHODS

### 2.1. Data and information

The Lancang-Mekong River originates in Qinghai Province (China) with a drainage area of approximately 810,000 km<sup>2</sup> and flows southward through six countries. It eventually discharges into the South China Sea. The Lancang-Mekong River, with a total length of about 4,909 km and an average annual flow of 14,500 m<sup>3</sup>/s (Wang *et al.* 2017), is the seventh longest and the eighth largest river in the world with reference to mean annual discharge (Meade 1996). It is also the third longest river in Asia. The portion of Mekong River in China is the Lancang River, which accounts for 21% of the total area. Together with

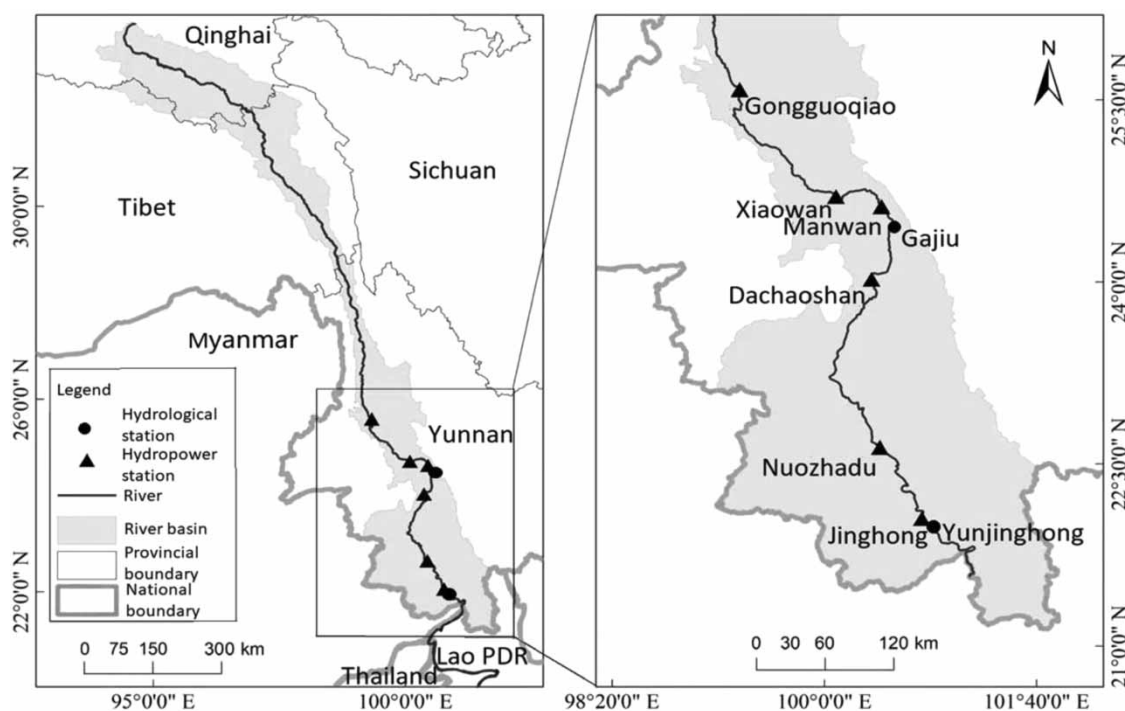
eastern Myanmar, it forms the upper reaches of the Mekong River, i.e. the Upper Mekong. The lower reaches overlapping Laos, Thailand, Cambodia and Vietnam are known as the Mekong River, i.e. the Lower Mekong (Gu *et al.* 2020).

The Lancang River drains a total area of 168,000 km<sup>2</sup>. The middle and lower reaches of the Lancang River are located in Yunnan Province with a drainage area of 88,600 km<sup>2</sup> (Liu & He 2012), accounting for 53% of the total Lancang. This section of the river is located in the zone of subtropical monsoon climate and lies in a humid climate zone with distinct flood season from June to October. In recent decades, the Lancang River has been experiencing great changes because of dam construction. The first Manwan dam was completed in 1993, after which Dachaoshan, Jinghong, Xiaowan, Gongguoqiao and Nuozhadu reservoirs were completed one after another. Among them, Xiaowan and Nuozhadu are the two main reservoirs with regulating function, which play an important role in the regulation of downstream runoff. By the end of 2013, all six main reservoirs have all been completed and put into operation. The location of reservoirs in the study area is shown in Figure 1. The detailed information of cascade reservoirs of Lancang River is listed in Table 2.

Data in this study include the annual precipitation, runoff and suspended load of Gajiu and Yunjinghong stations from the 1960s to 2019, as is shown in Table 3. The hydrological data includes monthly streamflow and sediment discharge of the two gauging stations in the middle and lower reaches of the Lancang River (Figure 1). The data used in this paper were obtained from Yunnan Hydrology and Water Resources Bureau and were all the results of national hydrological stations. The hydrological stations of Lancang River adopt standardized national standards. According to the code for measurement of suspended load in open channels (2015), sediment data at different depths on the vertical line are obtained by using the depth integration method and the vertical distribution of sediment concentration is more detailed. Therefore, the calculated average concentration of suspended sediment load has smaller error and higher accuracy compared with the data measured from the Lower Mekong using a single-point method (Hou *et al.* 2020). With the construction of new hydropower dams, the hydrological regime and suspended load in the middle and lower reaches have changed greatly. Therefore, there is an urgent need to reassess the changes in discharge and suspended load of Lancang River over the period extending from the early 1960s until the late 2010s.

## 2.2. Double mass curve

The method of double mass curve is quite simple, but very practical, and is widely used in the analysis of the consistency between hydrological and climatic variables (Xin *et al.* 2015; Gao *et al.* 2017). Merriam first used this method to analyze



**Figure 1** | Location map of hydropower and hydrological stations in the study area.



**Table 2** | Basic information of cascade reservoirs in the Lancang River

Reservoirs	Operation time	Watershed area (km <sup>2</sup> )	Mean annual runoff (km <sup>3</sup> )	Mean annual sediment (km <sup>3</sup> )	Total storage (km <sup>3</sup> )	Active storage (km <sup>3</sup> )
Gongguoqiao	2011	97,300	31.1	0.0255	0.51	0.12
Dachaoshan	2001	121,000	42.3	0.0317	0.93	0.37
Manwan	1993	114,500	38.8	0.0300	0.92	0.26
Nuozhadu	2012	144,700	55.2	0.0379	22.4	12.3
Jinghong	2008	149,100	58.0	0.0391	1.14	0.25
Xiaowan	2008	113,300	38.5	0.0297	14.56	9.90

Sources: Fan *et al.* (2015), Kummu *et al.* (2010), Räsänen *et al.* (2012).

**Table 3** | Data of hydrological stations used in this study

Stations	Location	Period (year)	Drainage area (km <sup>2</sup> )	Average runoff (10 <sup>9</sup> m <sup>3</sup> )	Average suspended load (10 <sup>6</sup> t)
Gajiu	E100°27'N24°36'	1964–2019	108475	38.27	29.55
Yunjinghong	E100°47' N22°02'	1964–2019	141779	54.43	67.20

the consistency of precipitation data in the Susquehanna watershed of the United States (Merriam 1937), and Searcy then explained it theoretically (Searcy & Hardison 1960). This method can be used to make an estimation about the impact of climate change and human activities on the variation of runoff and suspended load (Zhang *et al.* 2018). It is a plot of the cumulative relationship between one variable versus another, which is high linearly related in a concurrent time (Gao *et al.* 2017). The double mass curve will be a straight line if the two variables are proportional to each other, and the slope of the line represents the ratio between them. Linear regression analysis is also used to analyze the hydrological time series.

Despite its widespread use, this method has its limitations. The trend changes and mutation points observed by naked eyes using double mass curve are usually subjective, so it needs to be verified with other abrupt change analysis. As hydrological data itself is prone to change, it may lead to the illusion of mutation points, so the hydrological data of sufficient time series is needed to get the accurate mutation point (Searcy & Hardison 1960). Double mass curve contains random errors that are difficult to determine, which is also the problem of all statistical models. Therefore, the analysis results of water and sediment changes are relatively rough (Mu *et al.* 2010).

### 2.3. Wavelet analysis

The wavelet analysis is a common means of detecting the periodicity and phase change of hydrological data with long time series. There are various wavelet types. It is necessary to find accurate discriminant signals according to the sequence characteristics, so as to improve the rationality and accuracy of the wavelet function. In the analysis of wavelet results, it is important to pay attention to the impact of edge effect on its accuracy to avoid pseudo-period and pseudo-trend (Sang *et al.* 2013). Among the many choices of wavelet functions, the Morlet wavelet with the form of periodic function is widely applied in the analysis of periodic oscillations (Issac *et al.* 2004; Labat 2005). Therefore, it is used to distinguish the periodic features of annual runoff at Gajiu and Yunjinghong stations in this paper. By means of wavelet transform analysis, wavelet coefficients and their variances are computed. When the wavelet coefficients are known, the multi-scale periodicity characteristics can further be obtained.

For a given hydrological time series  $f(t)$ , its wavelet coefficient  $W_f(a, b)$  is:

$$W_f(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \hat{\psi}\left(\frac{t-b}{a}\right) dt \quad (1)$$

where  $a$  and  $b$  are the scale and translation parameters, respectively, and  $\hat{\psi}(t - b/a)$  is the transfer function (i.e. a wavelet).

For practical applications, hydrologic time series are usually discrete, so the discrete form is:

$$W_f(a, b) = \frac{1}{\sqrt{a}} \Delta t \sum_{k=1}^N f(k\Delta t) \hat{\psi}\left(\frac{k\Delta t - b}{a}\right) \quad (2)$$

where  $k = 1, 2, \dots, n$ , and  $\Delta t$  is the time interval.  $W_f(a, b)$  varies with  $a$  and  $b$ . Take  $b$  as the abscissa and  $a$  as the ordinate to plot a two-dimensional contour map about  $W_f(a, b)$ , then the real part contour map of wavelet coefficients is obtained.

The wavelet variance is the integral of the square of all wavelet transform coefficients in the time domain with respect to scale  $a$  and represents the energy of periodic fluctuations at scale  $a$ . Its formula is:

$$Var(a) = \int_{-\infty}^{+\infty} |W_f(a, b)|^2 db \quad (3)$$

## 2.4. Abrupt change analysis

The mathematical method of second-order difference of regression coefficient combined with double mass curve is used to determine the accurate point of abrupt change. The combination of the two methods has two main advantages in the analysis of abrupt change. First, the data used in this paper is the longest and latest time series to date, which lays the data foundation for double mass curve and abrupt change analysis. It can help to get more accurate results as both methods require data of long enough time series. Secondly, the double mass curve can eliminate the impact of runoff on the suspended load, and then the mutation point can be calculated accurately using the mathematical method.

In the double mass curve of accumulative runoff and suspended load, it tends to rise gradually, then suddenly accelerate or decelerate and flatten out after a certain point. The 'turning point' of this mutation is an important characteristic point, which demonstrates the change in water resources and sediment transport. Therefore, it is of great significance to determine the change point accurately. The monotonicity and unevenness of the double mass curve are single. In order to find the point of slope change, the second-order difference of regression coefficient is used to calculate the abrupt change point, and then the year of abrupt change in the cumulative relationship between discharge and suspended load can be determined. The method of abrupt change requires the data to be equally and closely, i.e. enough data is needed to avoid the edge effect. The edge effect will make it difficult for the calculated regression coefficient to represent the slope of the curve well. In this paper, 56 years of long-term series data is used in the following calculation and this problem can be avoided. The specific steps of the calculation are as follows.

The points in the double mass curve of runoff and suspended load were selected as exploration points to form a sequence. With each exploration point as the center, data (before and after the exploration) with the same number ( $n$ ) were taken to construct a sliding window. Furthermore, the front and back slopes are compared under the same conditions. Here,  $n = 2, 3, 4$  are used to construct three sets of sliding windows for calculation. Specifically, in the sliding window constructed by  $L_i$ , linear regression is performed on the  $n$  data points before (or left) the exploration point, and the corresponding regression coefficient is obtained as  $b_l^{(n)}(L_i)$ ; similarly, for the  $n$  data points after the exploration point (or right), the corresponding regression coefficient is recorded as  $b_r^{(n)}(L_i)$ . Considering that with a larger  $n$ , the regression coefficient calculated reflects better slope shape, less randomness and greater statistical significance. Thus, when  $n = 2, 3, 4$  and the weight value is  $n^2$ , the method of weighted average is used to calculate  $b_l^{(n)}(L_i)$  and  $b_r^{(n)}(L_i)$ . Then, when  $b_j^{(2)}(L_i)$ ,  $b_j^{(3)}(L_i)$ ,  $b_j^{(4)}(L_i)$  ( $j = l, r$ ) all exist for a certain  $L_i$ , the weighted average is:

$$\bar{b}_j(L_i) = \frac{1}{2^2 + 3^2 + 4^2} [2^2 \times b_j^{(2)}(L_i) + 3^2 \times b_j^{(3)}(L_i) + 4^2 \times b_j^{(4)}(L_i)] \quad (j = l, r) \quad (4)$$

For each exploration point  $L_i$ , the difference calculated between  $\bar{b}_l(L_i)$  and  $\bar{b}_r(L_i)$  is recorded as

$$\Delta S(L_i): \Delta S(L_i) = \bar{b}_l(L_i) - \bar{b}_r(L_i) \quad (5)$$

$\Delta S(L_i)$  is the first-order difference for the slope of the curve before and after the exploration point, which can also be understood as the variation of the slope of the curve before and after point  $L_i$ . Its size reflects the magnitude of the change in the slope of the curve at point  $L_i$ .

Subsequently, the second-order difference for the sequence of  $\Delta S(L_i)$  is calculated, i.e.:

$$\Delta S^2(L_i) = \Delta S(L_{i-1}) - \Delta S(L_i) \quad (6)$$

$\Delta S^2(L_i)$  as well constitutes a sequence whose magnitude reflects the acceleration of the slope change of the curve between the interval  $(L_{i-1}, L_i)$ . According to the sequence of  $L_i$  from small to large, find out the maximum value in the sequence of  $\Delta S^2(L_i)$  (its absolute value is greater than the previous or subsequent  $n$  values), and the corresponding interval is the interval where the slope change point is located.

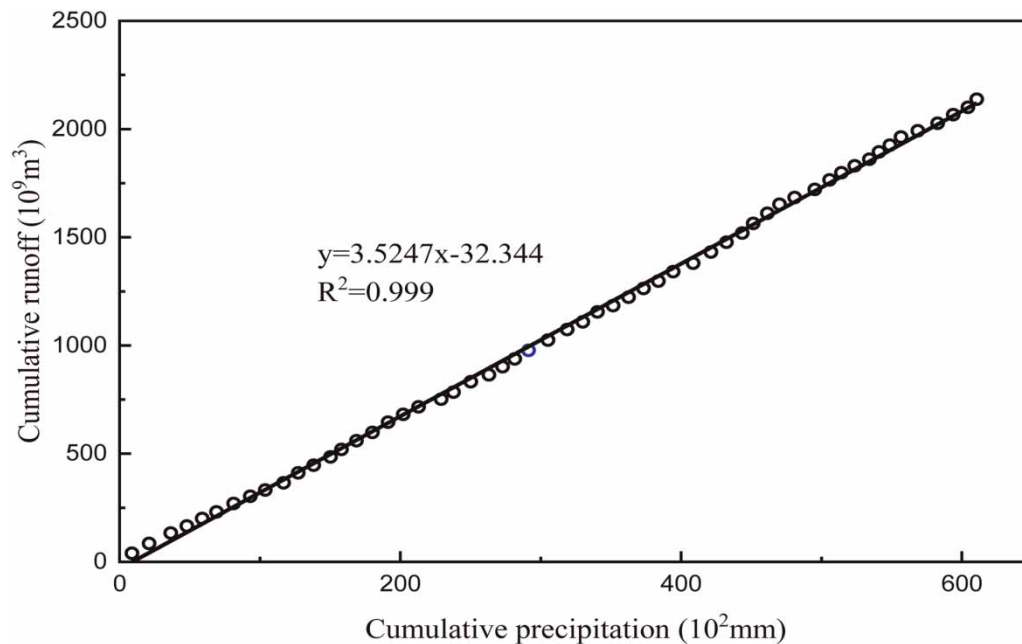
### 3. RESULTS AND DISCUSSION

#### 3.1. Variation of runoff

##### 3.1.1. Relationship between annual runoff and climate change

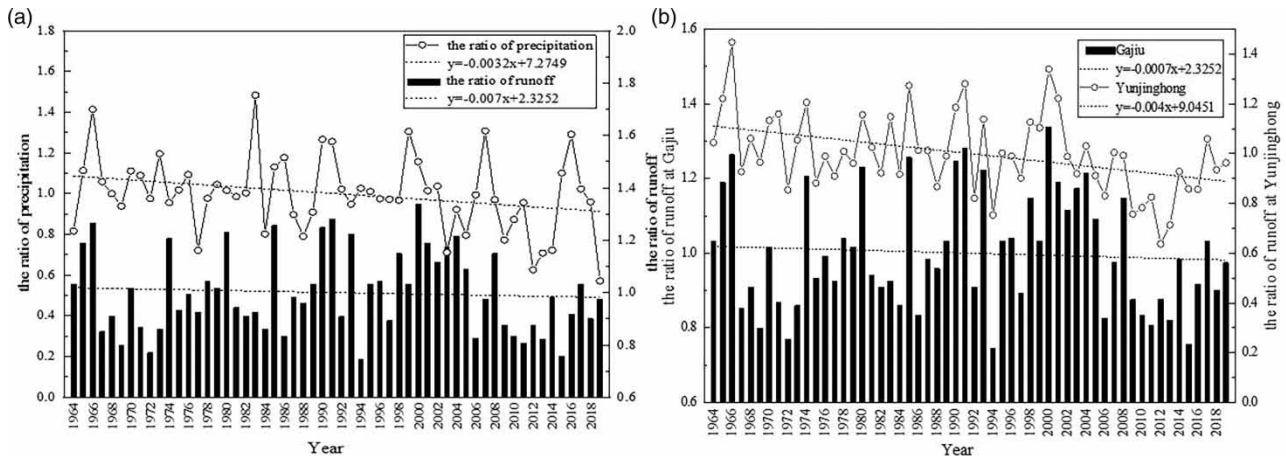
Double mass curve is used to explore the relationship between the accumulation of precipitation and runoff of Gajiu station. As is shown in Figure 2, the annual cumulative precipitation and runoff of Gajiu station exhibit a nearly perfect linear relationship with  $R^2 = 0.999$ . This directly demonstrates that there is a high correlation between runoff and precipitation. As precipitation is dominated by climate change, it can be deduced that the variation of runoff is mainly affected by climate change.

In the lower reaches of Lancang River, the average annual precipitation during 1964–2019 is 1,090.34 mm, and the annual precipitation at Gajiu station varies between 623.00 and 1,618.00 mm. From 1964 to 2019, the average annual runoff is  $3.82 \times 10^{10} \text{ m}^3$  and ranges from a minimum value of  $2.85 \times 10^{10} \text{ m}^3$  in 1994 to a maximum one of  $5.11 \times 10^{10} \text{ m}^3$  in 2000. The annual runoff of Yunjinghong station ranges from  $3.47 \times 10^{10} \text{ m}^3$  in 2012 to  $7.87 \times 10^{10} \text{ m}^3$  in 1966 with a mean value of  $5.44 \times 10^{10} \text{ m}^3$ . Figure 3 shows the trends of annual precipitation and runoff in the study area based on linear regression analysis for 56 years. The dot plot and histogram in Figure 3(a) represent the trends of annual precipitation and runoff of Gajiu station, respectively, while the corresponding interpolation lines represent their equations of linear



**Figure 2** | Double mass curve of annual precipitation and runoff at Gajiu station.





**Figure 3** | (a) Temporal variations of annual precipitation and runoff at Gajiu station. (b) Temporal trends of annual runoff at Gajiu and Yunjinghong stations.

regression analysis. In Figure 3(b), the two types of graphs and interpolated lines represent the changes of annual runoff and its regression analysis at Gajiu and Yunjinghong stations, respectively. Here, for the sake of data confidentiality, plots are drawn using the ratio of annual average value to the multi-year average value for each variable, as well as subsequent plots. The annual precipitation showed a trend of slight decrease and there was also a decreasing trend in annual runoff, but not notable. The decrease in annual runoff of Yunjinghong station was more significant than that of Gajiu station. The annual runoff of Yunjinghong station slightly exhibited a downward trend and the inter-annual variation of runoff also showed small fluctuations, which was basically consistent with that of Gajiu station.

As is seen from Figure 2, there is a very high linear correlation between cumulative annual runoff and precipitation, which is almost close to 1. With respect to the long time series of runoff and precipitation in Figure 3(a), the fluctuations and tendencies of the two are also highly consistent. This indicates that the change of precipitation was the main reason for runoff change, which is also consistent with the study of Liu *et al.* (2018). In addition, the linear analysis in Figure 3(a) tells that the total amount of runoff basically showed little change in the long-term series. It can be concluded that dam construction had little effect on the total amount of runoff. However, there were several years in which runoff and precipitation showed different changes, such as 1993 and 2003. This may be temporarily affected by dam construction; that is, the river closure.

### 3.1.2. Impact of reservoirs on the annual process of runoff

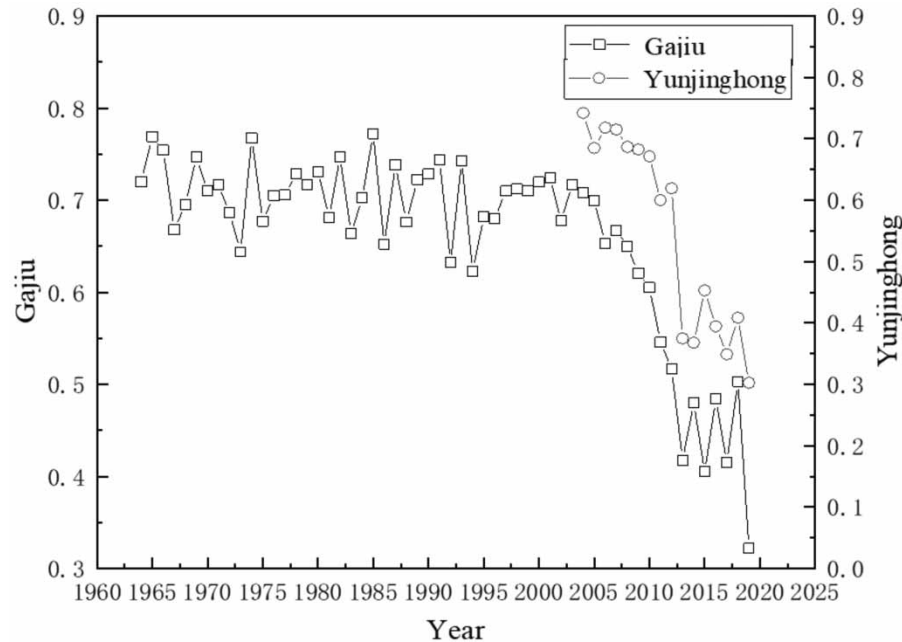
The multi-year averages of the monthly runoff at Gajiu and Yunjinghong stations were analyzed to further understand the seasonal changes in the lower reaches of Lancang River (Table 4). Figure 4 exhibits the changes of runoff at the two stations during the flood season (from June to October). It can be seen that the ratio of runoff in flood season at Gajiu station exhibits an obvious decrease after 2009 and a decrease value of 22.64% is calculated according to Table 4. As for Yunjinghong station, the average annual runoff in flood season during 2004–2012 and 2013–2019 was  $3.86 \times 10^{11} \text{ m}^3$  and  $2.22 \times 10^{11} \text{ m}^3$ , respectively, accounting for 68.42 and 37.67% of the average annual runoff. Analysis indicates that there is an obvious trend of runoff diffusion from flood season to non-flood season. This is because water during the flood season is stored in the reservoir and released downstream when the dry season arrives, altering the intra-annual variation of runoff.

As a result, the intra-annual variation of runoff is mainly affected by reservoirs, especially Xiaowan and Nuozhadu reservoirs, because they are both the kind of reservoirs with regulating effect as mentioned before. Moreover, the years 2008 and

**Table 4** | Comparison of runoff in the flood season

Period	Gajiu ( $10^9 \text{ m}^3$ )	Period	Yunjinghong ( $10^9 \text{ m}^3$ )
1964–2008	468.60(70.72%)	2004–2012	385.88(68.42%)
2009–2019	406.20(48.08%)	2013–2019	221.88(37.67%)

The percentage in parentheses represents the ratio of runoff in the flood season during the year.



**Figure 4** | Runoff during the flood season at Gajiu (1964–2019) and Yunjinghong (2004–2019) stations.

2012 were exactly the time when Xiaowan and Nuozhadu reservoirs were completed and put into use. It was also the time when the runoff in flood season of the two stations began to show significant declines. Therefore, reservoirs like Manwan and Jinghong had little influence on the intra-annual variation of runoff.

Combined with the previous analysis, it can be concluded that the reservoir exerted little impact on the total amount of runoff, but mainly affected the annual process. The amount of runoff was dominated by climate change, while seasonal redistribution was controlled by reservoirs.

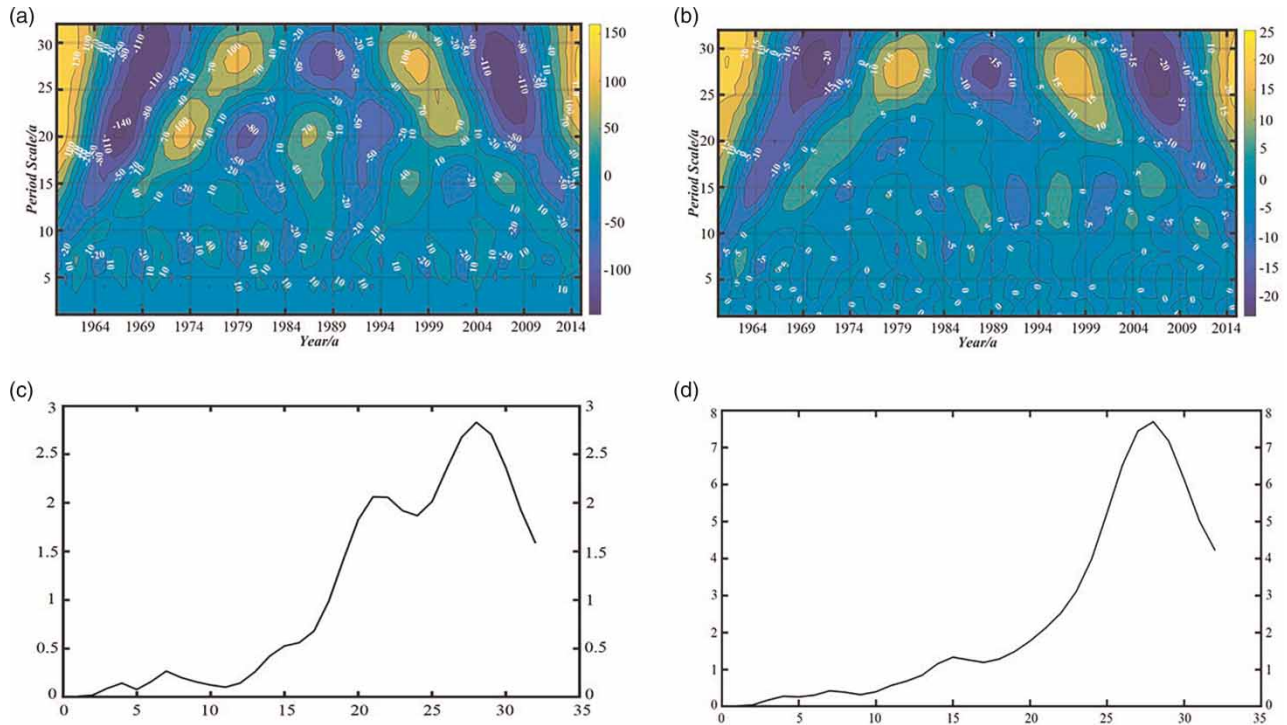
### 3.1.3. Periodicity of runoff variation

The multi-time scale periodicities of runoff at Gajiu and Yunjinghong stations were presented by Morlet wavelet analysis. Figure 5(a) and 5(b) shows the real parts of wavelet coefficient through the contour maps and the wavelet variance is shown in Figure 5(c) and 5(d). The graph of wavelet variance can reflect the distribution of fluctuation amplitude for the annual runoff time series on a certain scale. It can be used to identify the intensity of perturbation and periodic characteristics of various scales in the time series, and then determine the main cycle of annual runoff evolution. Thus, with the help of Figure 5, it is easy to identify the amplitude of periodic fluctuations during the long-term series.

According to Figure 5, the periodic behaviors of the two stations are determined in Table 5. It can be seen from Figure 5(c) that there are four obvious peaks in the wavelet variance graph of Gajiu station, corresponding to the time scales of 4, 7, 21, and 28 years, respectively. Among them, the time scale of about 28 years corresponds to the maximum peak, indicating that the periodic oscillation of about 28 years is the strongest. Therefore, it is concluded that 28 years is the first main period in the change of annual runoff. The time scales of 21, 7, and 4 years correspond to the second, third, and fourth peaks, which are the second, third, and fourth main periods, respectively. Similarly, the periodic characteristics of Yunjinghong station are obtained.

During the study period, the annual runoff at the two stations both exhibited four periodicities with the dominant period of 28 years. In particular, annual runoff at Gajiu station showed periods of 4, 7, 21 and 28 years, while at Yunjinghong station the periods are of 4, 7, 15 and 28 years. Combining the dominant period and the figure of the real parts process of wavelet coefficient (Figure 6), it can be seen from Figure 6 that the annual runoff at the two stations has undergone about three high and low flow periods at the characteristic scale of 28 years.

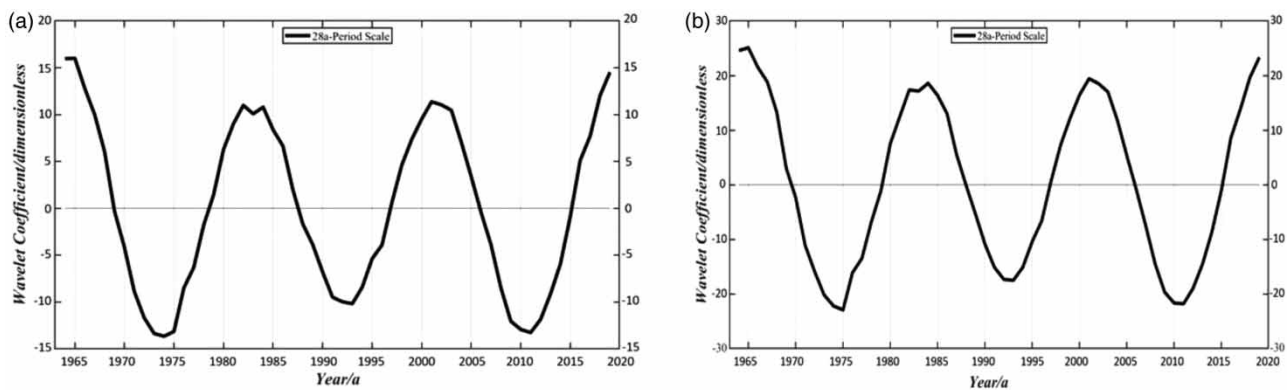
The periodic performance of runoff changes can help to determine the general trend of runoff changes in the future, which is of great help in understanding the changes in water resources and making judgments on the abundance and depletion of water resources.



**Figure 5** | (a,b) Contour maps of wavelet coefficients for the real parts at Gajiu and Yunjinghong stations. (c,d) Graphs of wavelet variance at Gajiu and Yunjinghong stations.

**Table 5** | Multi-periodicities of annual runoff

Stations	Multiple periodicities (year)	Dominant periodicity (year)
Gajiu	4, 7, 21, 28	28
Yunjinghong	4, 7, 15, 28	28



**Figure 6** | Real part process of wavelet under the characteristic time scale of the first main period. (a) Gajiu (b) Yunjinghong.

### 3.1.4. Impact of runoff variation on downstream areas

As mentioned before, the total amount of runoff did not change much, but its process exhibited great variation, which was mainly manifested as seasonal redistribution. After the operation of Xiaowan and Nuozhadu reservoirs, runoff during the year was redistributed with a decrease in flood season and an increase in dry season. That is because the two reservoirs both have a regulating effect and replenishment function. Water is stored in reservoirs during the flood season and released during the dry season. As a result, seasonal redistribution of runoff occurred and the process of runoff tended to be more stable throughout the year, which could have a more positive impact on the downstream areas.

The seasonal redistribution of runoff is mainly shown as a significant increase in dry season and a decrease in flood season. The reduction of runoff during the flood season can reduce the occurrence of floods and help the growth of vegetation along the riverside. At the same time, the increased runoff during the dry season will increase the flow into the lower basins. Therefore, the risk of water shortage and salt water intrusion in downstream areas will also be reduced (Kummu & Varis 2007). All of these show great benefits for irrigation and agricultural production in downstream areas. The seasonal redistribution of runoff also means a decrease in the water level during the flood season and an increase during the dry season, which has a direct effect on the improvement of navigational conditions in the whole river. Finally, the Lancang cascade has a great influence on the hydrological regime of the Lower Mekong. In Laos, Thailand and other downstream countries, the runoff of Lancang River accounts for the major proportion of the dry season flow. This helps maintain the stability of water resources and contributes to the urban and industrial development in these countries. With the completion of Xiaowan and Nuozhadu hydropower stations, the prospect for exporting generated power to external markets in Laos, Thailand and Myanmar will soon become a reality (Adamson 2001; Huong 2021). To sum up, the seasonal redistribution of runoff improves the resource reliability of the entire Lancang-Mekong River system, which has many benefits to the national economy and livelihood of downstream countries and regions.

## 3.2. Response of suspended load to reservoirs

### 3.2.1. Inter-annual variation of suspended load

Figure 7 shows the trends of suspended load at the two stations during the study period. The average annual suspended load of Gajiu station during this time is  $2.89 \times 10^7$  t. The maximum annual suspended load occurs in 1991 with a value of  $9.05 \times 10^7$  t and the minimum one is  $2.25 \times 10^5$  t in 2013. The mean annual suspended load of Yunjinghong station is  $6.72 \times 10^7$  t with a range from  $3.82 \times 10^5$  t in 2014 to  $1.81 \times 10^8$  t in 1991. It can be clearly seen from Figure 7 that the suspended load of the two stations show similar tendencies and both exhibit obvious stage characteristics.

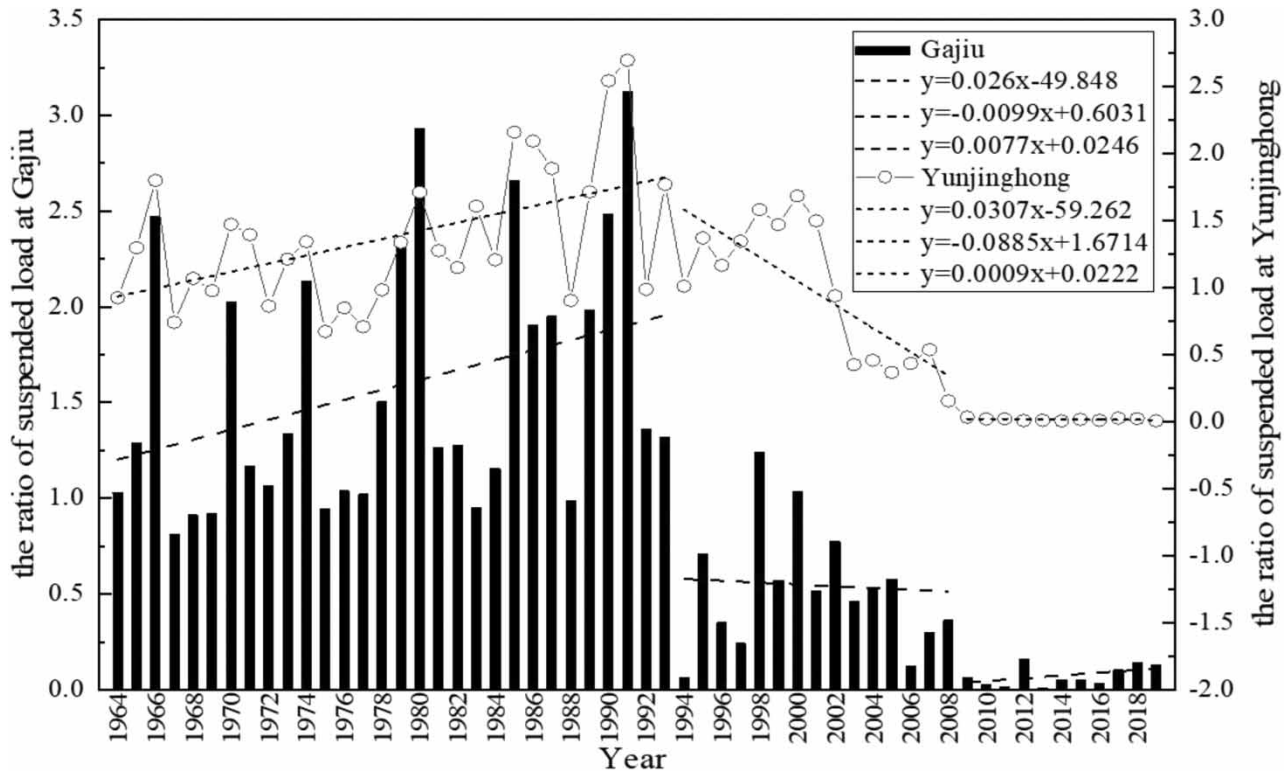
Suspended load shows consistent fluctuations compared with runoff, but it also exhibits a sharp downward trend and obvious change in stages. This demonstrates that climate change has little influence on the reduction of suspended load, and the main cause comes from human activities.

As for the double mass curve of the cumulative annual runoff and suspended load, suspended load shows sharp declines and there are both clear trends of change at the two stations (Figure 8). It can be seen that there are two turning points at which the accumulated suspended load suddenly decreased with the accumulation of runoff. According to the two turning points, the entire time series can be divided into three periods, which are the pre-change period (P0), post-change period 1 (P1) and post-change period 2 (P2). The slope of the linear regression is lower in P1 and it was much lower than that of P1 in P2. Moreover, the line is almost horizontal in P2. This indicates that for the same amount of cumulative runoff, the resulting suspended load during P1 is less than that during P0, and this situation also appeared in P2. All these indicate that suspended load exhibits sharp declines at different stages. Therefore, the next step of our work is to identify the turning points by means of abrupt change analysis and explicitly divide the time series into three periods for further analysis.

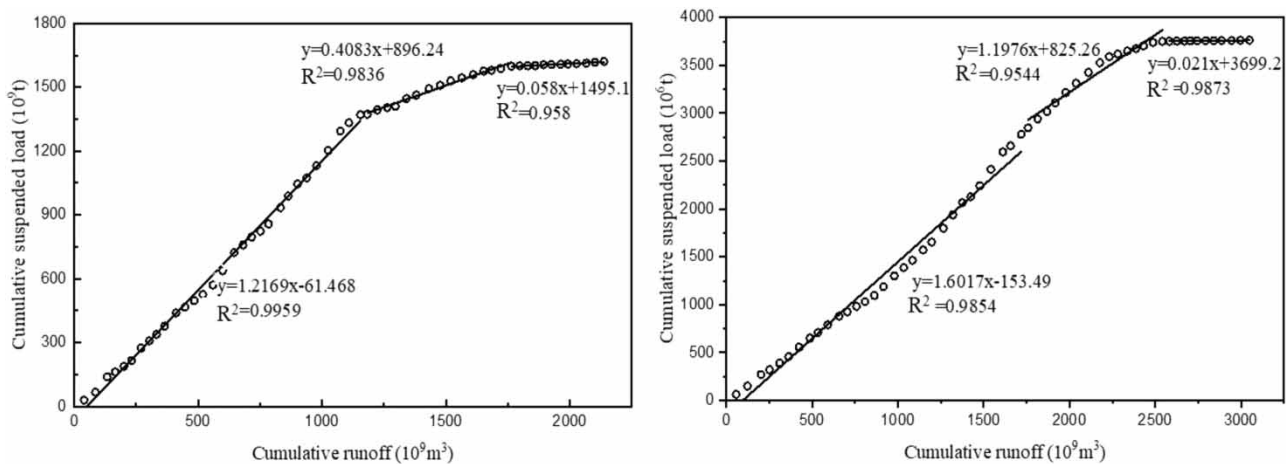
### 3.2.2. Abrupt change of suspended load

The second-order difference of regression coefficient is used to determine the turning points based on the double mass curve of cumulative runoff and suspended load. According to the computational results, the intervals of  $\Delta S^2(L_i)$  with the maximum absolute value are identified as 1992–1993 and 2007–2009 of Gajiu and Yunjinghong stations, respectively. Combined with the double mass curve of annual suspended load and runoff, 1993 and 2008 are determined as the turning points at which the overall trend of the curve changes. Double mass curve is used in abrupt change analysis to eliminate the effect of discharge variation (Liu *et al.* 2013a, 2013b). There were some local turning points before 1993 at Gajiu station and before 2008 at Yunjinghong station, such as 1987, 1984, 1979 and 2003. In these years, the trend of the curve also changed but it was not





**Figure 7** | The trends of suspended load at Gajiu and Yunjinghong stations.



**Figure 8** | Double mass curve of annual runoff and suspended load at Gajiu and Yunjinghong stations.

sustainable. Therefore, we finally divide the entire time series into three periods with 1993 and 2008 as turning points. That is, data from 1964 to 1993 are considered as pre-change period (P0), data from 1994 to 2008 are considered as post-change period 1 (P1) and data from 2009 to 2019 are considered as post-change period 2 (P2).

As we know, 1993 is exactly the operation time of Manwan reservoir, and 2008 is that time of Xiaowan and Jinghong reservoirs. Thus, we can extrapolate preliminarily that the changes of suspended load are mainly affected by the construction of the two reservoirs. Comparison and analysis before and after dam construction in the next section will help us understand better about the impact of reservoirs.



### 3.2.3. Comparison of suspended load before and after reservoir construction

Variations of suspended load of Gajiu and Yunjinghong stations before and after reservoir construction are listed in Table 6. The mean annual suspended load of Gajiu station is  $2.96 \times 10^7$  t with average values of  $4.61 \times 10^7$  t,  $1.65 \times 10^7$  t and  $2.09 \times 10^6$  t for each period, respectively. During P1 and P2, suspended load decreased by 64.37 and 95.47% compared to that during P0, respectively. The average annual suspended load of Yunjinghong Station is  $6.72 \times 10^7$  t, and the mean annual suspended load for the three periods is  $9.27 \times 10^7$  t,  $6.47 \times 10^7$  t and  $1.13 \times 10^6$  t, respectively. Compared with the pre-change period, the average annual suspended load in P1 and P2 decreased by 30.16 and 98.78%, respectively. These data indicate that the amount of suspended load has decreased significantly since 1994 and a notable drop also occurred after 2012. The amount of suspended load in the study area has now dropped to a very low level, almost none. However, the mean annual precipitation and runoff show different changes from suspended load, which illustrates that the decrease of suspended load is mainly caused by human activities (as dam construction, soil erosion, the change of land use, and so on). Sediment is most intercepted by the dam, and a large amount of sediment is deposited in the reservoir. Other factors also contribute to the loss of sediment to a certain degree.

It can be seen that before and after the construction of reservoirs, the average annual runoff decreases slightly while the average annual suspended load shows significant declines, which demonstrates that human activities exert much more impacts on suspended load than on runoff.

### 3.2.4. Impacts from the changes of suspended load

Based on the foregoing analysis, the construction of reservoirs and dams has an important impact on suspended sediment transport. Suspended sediment has shown a significant decline with dam construction, which is 95.47–98.78% less than before the construction of reservoirs. Given that the six dams built in the Lancang River are mainly used for hydropower generation, it can be assumed that most of the sediment was intercepted by the reservoir. With a large amount of sediment deposited in the reservoir, the storage capacity of reservoirs will be reduced, which will affect the performance of normal function for the reservoir. Therefore, it is of great significance to reduce sedimentation in the reservoir. The sedimentation in the reservoir will also lead to erosion in the downstream river. However, due to the offsetting effect of downstream tributaries, specific changes in the channel geomorphology of downstream river needs to be further studied based on detailed data.

## 3.3. Discussion

The temporal changes of inter- and intra-annual runoff and suspended load from 1964 to 2019 at Gajiu and Yunjinghong stations were analyzed by double mass curve and abrupt change. The runoff exhibited a slight downward trend in the long term while suspended load dropped sharply in 1993 and 2008. Then the quantitative changes of suspended load and runoff in flood season were analyzed in different periods. The impacts of reservoir construction and climate change were also evaluated. The method of Wavelet analysis was adopted to determine the periodic behaviors of runoff. The main results are presented as follows.

### 3.4. Runoff change and cause analysis

It can be seen from Figure 3 that the annual runoff of both Gajiu and Yunjinghong stations show a slight decreasing trend in the long time series. The decreasing trend of Yunjinghong is more obvious than that of Gajiu. In terms of inter-annual variation, the annual runoff exhibits great fluctuations during the study period, but there is no clear abrupt change in long-term variation. The cumulative values of annual precipitation and runoff are highly consistent, as shown in Figure 2. On the whole,

**Table 6** | Variations of suspended load at Gajiu and Yunjinghong stations

Period	Gajiu ( $10^6$ t)	Yunjinghong ( $10^6$ t)
1964–1993 (baseline)	46.18	92.67
1994–2008	16.45(−64.37%)	64.72(−30.16%)
2009–2019	2.09(−95.47%)	1.13(−98.78%)
1964–2019	29.55	67.20

The percentage in parentheses represents the ratio of mean annual suspended load to that in the baseline period.

the fluctuations and tendencies of runoff are basically consistent with the variation of precipitation as shown in Figure 3. All these suggest that the main reason for the slight decrease in runoff during 1964–2019 is climate change, especially precipitation. The fact that the total amount of runoff has barely changed illustrates that dam construction has little effect on the total runoff. Other studies about precipitation and runoff mainly focused on the trend changes of runoff and explained that precipitation was the main cause of runoff changes (Liu *et al.* 2018), which is consistent with this study. Based on the qualitative analysis, this paper further gives the quantitative changes in seasonal redistribution of annual runoff by using the latest long-term data.

Although the change of annual runoff in the long time series was not significant, its intra-annual distribution changed considerably, as is shown in Figure 4. The runoff in flood season of the two stations both exhibited great declines. The runoff of Gajiu decreased significantly after the completion of Xiaowan reservoir in 2008, while runoff of Yunjinghong showed an obvious decline after the operation of Nuozhadu reservoir in 2012. This is because reservoirs store water during the flood season and release it during the dry season. Data comparison shows that before and after the construction of Xiaowan and Nuozhadu reservoirs, the proportions of runoff in flood season at the two stations decreased by 22.64 and 30.75%, respectively.

As mentioned before, the seasonal redistribution of runoff caused by reservoir operation brings many benefits. However, there are also some adverse effects and it is responsible for downstream droughts to some extent. The frequency and severity of droughts in the Mekong River basin has increased in the past few decades according to recent studies of Mekong River Commission (MRC). Even during the rainy season, water levels of the Upper Mekong are still at its lowest in history. Experts from the MRC believe that there are three main reasons for the low water level in the entire basin, namely reduced rainfall, reduced discharge from Jinghong dam and high temperatures. Therefore, the impact of hydropower dams in upstream China on drought is undeniable in drought years (UCH LEANG 2020) and the actual extent of the impact remains to be studied further. Although the construction of hydropower dams in China would cause drought in downstream areas to a certain extent, its important role in flood prevention, drought resistance as well as the improvement of flood control and water supply conditions cannot be ignored. For example, the Mekong River suffered a drought in 2016, and Vietnam experienced its worst drought in 90 years. To alleviate the severe drought in the Mekong River, China increased the discharge flow from Jinghong power station despite the fact it was also impacted by the drought. The accumulated amount of water delivered downstream from Lancang hydropower station increased by 94% compared with the natural inflow, which effectively improved the water supply conditions in the dry season and had a significant effect of regulating abundance and replenishing depletion.

The periodicity of runoff variation in long time series was identified by Morlet wavelet analysis. The first dominant period for both the two stations was 28 years. The second, third and fourth dominant periods of annual runoff were 4, 7, 21 and 4, 7, 15 years, respectively. The periodic analysis of runoff can reveal the characteristics of annual runoff evolution in the middle and lower reaches of the Lancang River over a certain period of time. The periodic performance of runoff change can also help to judge the general trend of runoff change in the future, which is of great help in understanding the dynamic change of water resources and making predictions about its abundance and depletion. It can further provide guidance for the comprehensive utilization of water resources and offer references for leaders to make relevant decisions on the operation of reservoirs.

### 3.5. Abrupt change of suspended load

It can be seen from Figure 7 that in the long time series, the annual suspended load of both stations showed a distinct downward trend as described in Walling (2008). It also exhibited sharp decreases in stages with obvious turning points as is shown in Figure 8. Based on the curve of accumulative runoff and suspended load, analysis of abrupt change was conducted and the turning points of suspended load were determined as 1993 and 2008. The time of abrupt change in suspended load corresponds well to the time of reservoir construction. The first reservoir, Manwan, was completed and operated in 1993, while Jinghong and Xiaowan reservoirs were put into operation in 2008. A large amount of sediment was trapped in reservoirs during the process of water storage, and suspended load before and after reservoir operation was then compared. According to the turning points, we divided the time series into three periods, P0, P1 and P2, and compared the data series of different periods. The annual suspended load of Gajiu and Yunjinghong stations during P1 and P2 decreased by 64.37–30.16% and 95.47–98.78% compared with that during P0. After the construction of Manwan reservoir, its impact on suspended load of Yunjinghong was much less than that of Gajiu, and after Jinghong, Xiaowan and Nuozhadu reservoirs all completed, suspended load of Gajiu and Yunjinghong dropped by 95.47–98.78% compared with that before reservoir construction. It can be

indicated that the amount of suspended load in the Lancang River is now very low and a large amount of sediment has been deposited in the reservoir.

Liu *et al.* (2013a, 2013b) conducted a study on the changes of suspended load in the Lancang-Mekong River during the period of 1964–2003, and they determined the mutation points as 1984 and 1993 by using the double mass curve. They divided the time series into three periods, and the changes of suspended load can be characterized by a trend of ‘stable-increase-decrease’ during the three periods. The main influencing factors that were concluded are serious soil erosion as well as the construction and operation of Manwan hydropower station. Both the two studies agree that the interception of Manwan reservoir led to a sharp drop in suspended load after 1993, and other factors such as soil erosion also had a certain impact. However, since the time series used in this article is longer, the mutation points of 1993 and 2008 identified were the most significant. The year 1984 was not considered as a mutation point because it is less pronounced than the years 1993 and 2008. On the basis of abrupt change and cause analysis, the quantitative variation of suspended load in each period is further determined in this study.

The reduction of suspended load is much more profound than the change of runoff, indicating that suspended load is source-limited rather than transport-limited. As suspended load exhibited corresponding decreases with the construction of reservoirs, it's apparent that reservoir construction was the dominant factor of sediment variations. Other factors such as soil erosion and land use change may also play a role. All these analyses provide the managers with an accurate understanding of the current status of the Lancang River. Therefore, they can be more aware of the problems they may face and make better decisions about resource allocation and reservoir operation. One of the problems is concerned about reservoir siltation and three suggestions are put forward as follows. First, regular topographic surveys should be carried out on the main and tributaries to discover potential problems in time. Second, we should attach importance to soil and water conservation and adhere to the operation mode of reservoir ‘storing clear and releasing muddy’. Finally, sediment observation and analysis work should be carried out in a timely manner to predict sediment problems in reservoirs and further guide the operation of hydropower stations.

#### 4. CONCLUSION

Precipitation, runoff and suspended load in the Lancang River during 1964–2019 were analyzed by wavelet analysis, double mass curve and abrupt change analysis. The periodicities of runoff were calculated by Morlet wavelet analysis. According to the curve of cumulative runoff and suspended load, the turning points of suspended load were determined as 1993 and 2008, respectively. Based on the turning points, we divided the time series into three periods, P0, P1 and P2, and compared the data from different periods. The main conclusions are as follows.

Due to the influence of precipitation, the annual runoff of Gajiu and Yunjinghong stations showed a slight downward trend in the long time series, and the reservoir construction had little effect on it. The existence of reservoirs mainly affected the intra-annual distribution of runoff, resulting in a decrease of runoff in flood season and an increase in dry season. After Xiaowan and Nuozhadu reservoirs were put into operation, the proportions of runoff in flood season at the two stations decreased by 22.64 and 30.75%, respectively. This seasonal redistribution brings more benefits to the lower Mekong.

Since a large amount of sediment was intercepted during reservoir storage, the suspended load of the two stations also showed a significant decrease corresponding to the construction of reservoirs, and the abrupt change occurred in 1993 and 2008, respectively. The amount of suspended load in the Lancang River during P2 dropped by 95.47–98.78% compared with that before the reservoirs were constructed. At present, the suspended load that exists in the river is at a very low level. This significant drop in the suspended load of the river means that there is considerable siltation in the reservoirs, which should be taken seriously by reservoir managers.

The periodicities of runoff were calculated by Morlet wavelet analysis and the first dominant period of runoff at both was 28 years. Periodic analysis is helpful to predict the general trend of runoff change and thus understand the dynamic change of water resources. Impacts of changes in runoff and suspended load on downstream areas were also briefly explained. All these analyses enable this paper to provide a detailed and systematic presentation of the variations in runoff and suspended load as well as the current situation of the Lancang River. It is also of great help to the scientific research on the change of water and sediment in the Lower Mekong and the transboundary impacts from Lancang cascade reservoirs. Armed with this information, managers can make better decisions about resource allocation and reservoir operation, which will then maximize the interests of stakeholders throughout the whole Lancang-Mekong River basin.

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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